SHEAR WAVE ULTRASONIC TECHNIQUE AS AN NDE TOOL FOR COMPOSITE LAMINATES BEFORE AND AFTER CURING

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INTRODUCTION

The highly anisotropic elastic properties of the plies in a composite laminate, especially those manufactured from unidirectional prepregs, interact strongly with the in-plane vibration of shear ultrasonic waves propagating through its thickness[1-3]. The transmitted signals in a "crossed polarizer" configuration (with the transmitting and receiving transducers perpendicular to each other) were found to be particularly sensitive to ply orientation and layup sequence in a laminate[4,5]. This technique therefore holds good potential to be an NDE tool for detecting layup errors during the manufacturing of composite components. In such measurements, the transmitting transducer and the receiving transducer were rotated simultaneously, referred to as an azimuthal scan, while maintaining perpendicularity between them. The overall peak-to-peak amplitude of the RF waveform of the transmitted shear wave was recorded and plotted as a function of the transmitting transducer orientation. It was demonstrated experimentally that a single misoriented ply at the center of a 24-ply quasi-isotropic laminate can be detected with ease. Sensitivity to other errors in ply orientation and layup sequence have also been demonstrated.[6] To continue the assessment of detection sensitivity, 48-ply graphite-epoxy laminates with and without intentional ply errors were fabricated. Azimuthal scans were performed to detect the errors and the results were quite successful, as described below.

In order to understand the behavior of shear wave propagation in composite laminates and to interpret the test results observed experimentally, a model was developed.[4-6] The model was based on the decomposition of the shear polarization vector in a ply-by-ply manner through the thickness of the laminate. Experimental verification of the model was conducted using realistic 24-ply graphite/epoxy laminates. The behavior of the transmitted shear wave signal, especially its angular dependence, was modeled and compared with experiments for a number of transmitter and receiver directions. The agreement between experiment and model was generally satisfactory. Both model and experiment showed that shear wave transmission in the "crossed polarizer" geometry was highly sensitive to subtle errors and minor anomalies in ply orientation and layup sequence. Details of the model can be found in Refs. 4-6 and will not be repeated here. However, the model is used to further

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develop the shear wave technique in which the entire RF waveform is used instead of only the overall peak-to-peak amplitude. This leads to the concept of generating "fingerprints" for commonly-used composite layups. The "fingerprints" are two-dimensional images of the signal amplitude displayed as a function of time (abscissa) and transducer angle (ordinate). Different layups show different pattern when the received signals are displayed in this manner. Errors in ply orientation and layup sequence generally will also affect the pattern. Examples of changes in the "fingerprints" due to errors in laminate layup are given in a later section.

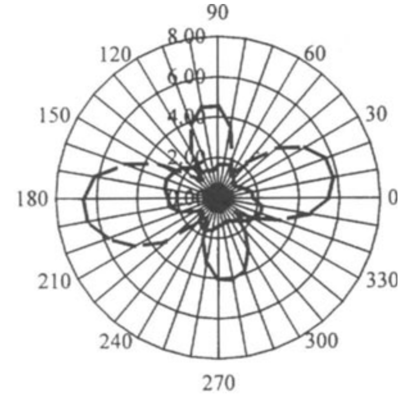
In the manufacturing of composites, it is important that errors be detected, and hence corrected, *before* the composite is cured. Nondestructive evaluation capabilities for "green" state composites are therefore highly desirable. Unfortunately, it is an area where existing capabilities are sparse and lacking. In this work, an effort is underway to develop shear wave techniques that can be applied to uncured composite layups. Since it is not feasible to rotate shear wave transducers on a stack of prepregs in their uncured state, a novel approach using electromagnetic acoustic transducers (EMAT) is employed. In this method the need for shear wave couplant is eliminated entirely. Some example results obtained on "green" stacks of prepregs are shown in a following section.

DETECTION SENSITIVITYFOR MISORIENTED PLIES

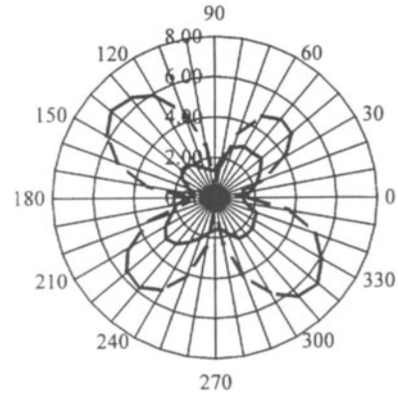
Quasi-isotropic layup is a commonly used laminate design in composite structure manufacturing. In the hand-layup of a quasi-isotropic laminate one has to lay down prepregs with their fiber directions along 0°, 90°, 45° and -45° orientations in the correct order. It is therefore more likely to make an error of 45 or 90 degrees than some small but visually detectable misalignment angle. To investigate the sensitivity for detecting a misoriented ply buried deeply in a quasi-isotropic laminate[4-6], experimental measurements and model calculations were carried out for $[(0/45/90/-45)_3]_S$ without any errors and with its 12th ply intentionally placed at 45° instead of -45°. The transmitted shear wave amplitude, as a function of the transmitter angle in the "crossed polarizer" configuration, was about 2-3 times greater in the panel with the error than that obtained on the panel without the ply orientation error.

To further investigate the detection sensitivity for a misoriented ply adjacent to the midplane but in a much thicker laminate, two 48-ply laminates of $[(0/45/90/-45)_6]_S$ layup were fabricated, one without any error and one with its 24th ply placed at 45° instead of -45°. The test results, shown in Fig. 1(a), easily distinguished the panel with the ply error from the one without it. Similar tests were also performed on two $[(0/90)_{12}]_S$ layups, one without any intentional error and the other with its 24th ply placed at 0^0 instead of 90°. The test results are shown in Fig. 1(b). Again, the presence of the ply error was easily detected.

It should be pointed out that the vector decomposition model predicted a null transmitted signal for the crossed polarizer geometry for $[(0/90)_{12}]_S$ when there were no misoriented plies. The transmitted signal would be exactly zero only in perfectly oriented laminates which, of course, cannot be achieved in any real life samples. In a thick composite, such as the 48-ply samples of Fig. 1, the cumulative effects of the unavoidable small angular errors that exist in all the plies can be substantial. The nonzero amplitude of the control laminate (solid line in Fig. 1(b)) is probably due to the cumulative orientation errors of the plies. The test results for the laminates with misoriented 12th ply (dashed lines in Figs. 1(a) and 1(b)) also showed distortions due to the small random orientation



(a)



(b)

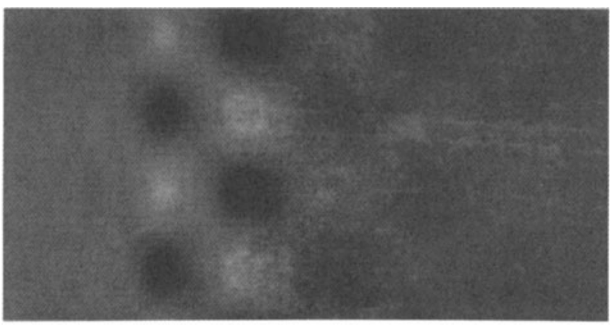
Fig. 1 Angular dependence of transmitted shear wave amplitude for 48-ply thick laminates: (a) quasi-isotropic layup $[(0/45/90/-45)_6]_S$, and (b) $[(0/90)_{12}]_S$ layup. The dashed lines indicate the results with the 24th ply misoriented by 90 degrees, and the solid lines represent the results without the misorientation error.

errors of the plies. For these laminates, the model predicts a four-pointed star with equal-length arms along the horizontal and vertical axes for $[(0/90/45/-45)_6]_S$(Fig. 1(a)), and a four-pointed star with equal-length arms oriented at 45 degrees from the horizontal and vertical axes for $[(0/90)_{12}]_S$ (Fig. 1(b)).

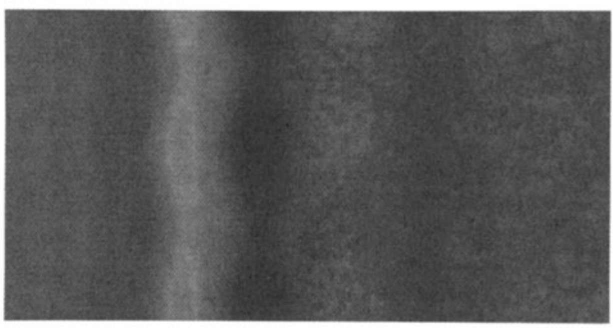
UTILIZING THE FULL WAVEFORM OF TRANSMITTED SHEAR WAVE

The angular dependence of the transmitted shear wave amplitude, such as those shown in Fig. 1, is based on the overall peak-to-peak amplitude of the signal. In doing so, one has ignored the information contained in the details of the RF waveform (i.e., the A-lines). Because the interaction of the polarization vector of the propagating shear wave and the fiber directions in the various plies can lead to very intricate cancellations and reinforcements in the RF waveforms, additional sensitivity for defect detection can be gained by displaying the full waveforms obtained in an azimuthal scan. One approach is to stack the various A-lines to form an image, with time as the horizontal axis and angle (of the transmitting transducer) as the vertical axis. The amplitude of the signal can then be displayed in a gray scale or using a color palette. Using the model to generate the transmitted signals, the resultant images are found to be different for different ply orientation and layup sequence among the commonly used laminate layup configurations. Furthermore, the presence of ply orientation errors and layup sequence anomalies are found to cause major changes in the images. Therefore, even though the degree of uniqueness is yet to be investigated, such angular-temporal displays of cross-polarized shear wave amplitudes may serve as “fingerprints” for detecting errors in laminates.

The top image in Fig. 2 shows the "fingerprint" of a symmetrized 24-ply laminate with a $[(0/45/90/\text{-}45)_3]_S$ layup. In contrast, the lower image is the "fingerprint" of $[(0/45/90/\text{-}45)_6]_T$, which is not symmetrized with respect to the midplane. The changes in the fingerprints are very striking and obvious. Using simulated data, other errors in ply misorientation and layup sequence have also been investigated. The results are generally encouraging.



$[(0/45/90/\text{-}45)_3]_S$



$[(0/45/90/\text{-}45)_6]_T$

Fig. 2 Model-predicted “fingerprints” of transmitted shear wave signal in a symmetric layup of $[(0/45/90/\text{-}45)_3]_S$ (top) and an asymmetric layup of $[(0/45/90/\text{-}45)_6]_T$ (bottom).

Experimentally the angle increments used in data acquisition should be small (a few degrees) in order to show the details of the "fingerprint" pattern. With shear wave couplant, it is very difficult to maintain a consistent coupling; manual data acquisition for the azimuthal scan is rather impractical. Possible solutions may include a motorized device to rotate the transducers, a computer for automated waveform acquisition, and, ideally, making use of EMATs that do not require couplant at all.

EMAT AND INSPECTION OF GREEN COMPOSITES

The distinct directionality of the fibers in each ply of a composite laminate interacts strongly with the polarization vector of a normal incidence shear wave. The angular dependence of a transmitted shear wave signal contain a wealth of information about the structure of the laminate and is sensitive to errors in ply orientation and layup sequence. When one tries to implement shear wave measurements on cured composite panels, however, several practical problems are encountered. First of all, the highly viscous shear wave couplant is inconvenient to use and can lead to irreproducibility in signal amplitudes. This is especially true when one had to rotate the transducer to acquire the angular dependence data. The measurements that are possible on cured composites would be very difficult on uncured green composites. Even if the couplant contamination problems can be solved by placing a metal foil over the prepregs, the rotation of the transducers would still be problematic.

To address the inspection problem of uncured composites, an effort was made in this work to take advantage of EMAT and develop a procedure that does not require shear wave couplant and is applicable to green composites. In this method, two EMATs produce normal incidence shear waves[7] on two aluminum blocks, which in turn are pressure-coupled to the uncured laminate using the natural "tack" of the uncured resin in the prepregs. The aluminum blocks serve several purposes. First, EMAT generation in aluminum is highly efficient due to the high electrical conductivity of the metal. Secondly, the blocks serve as acoustic delay lines to allow the receiver to recover. Finally, they provide a mechanical means to exert pressure on the green composite. Since there is no couplant between the aluminum and the EMAT probes, angular rotations can be easily achieved. The signal transmission through the pressure-coupled interfaces, although somewhat pressure dependent, remains constant during the experiment. A schematic diagram of the setup is shown in Fig. 3 and a disassembled view of the components is shown in Fig. 4. Two EMAT probes of 500 kHz were oriented perpendicular to each other and were used as the transmitter and receiver, respectively. The probes were rotated simultaneous while maintaining perpendicularity to each other to acquire the data of transmitted shear wave amplitude.

The EMAT technique has been applied to green composite laminates of a variety of layup. Figure 5 shows the results obtained from a 12-ply unidirectional stack of graphite epoxy prepregs. In the figure the dots are the experimental points and the solid line is the theoretical prediction in the form of ($\sin\theta \cos\theta$). The results showed good agreement between the experiment and the theory. Using the cross-polarized EMAT setup, the transmitted shear wave amplitude was also measured in two 12-ply cross-plied graphite-epoxy laminates: $[(0/90)_3]_S$ without any intentional error and $[(0/90)_3]_S$ with the 7th ply placed at 0°. The results, shown in Fig. 6, clearly show the large effect of the orientation error of the 7th ply on the transmitted signal.. Work is underway in a systematic and quantitative study of ply error detection in uncured composites using the EMAT technique.

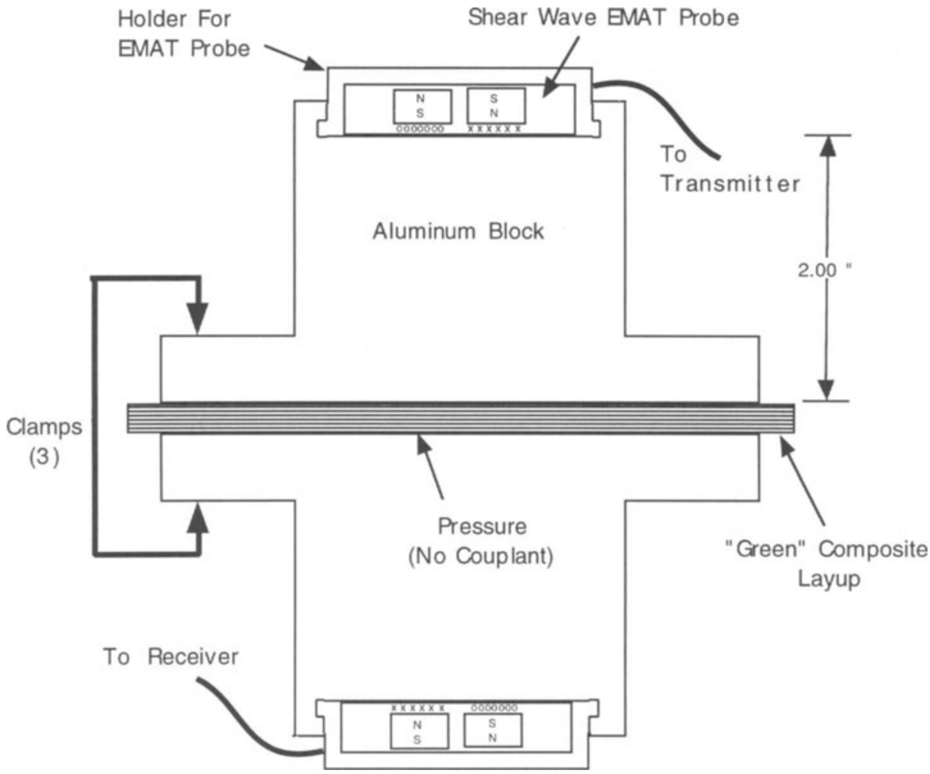


Fig. 3 Schematic diagram of the EMAT setup for inspecting uncured composite laminates.

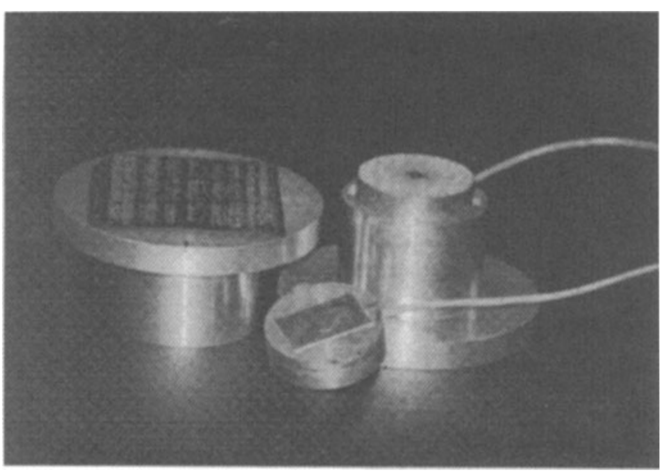


Fig. 4 Disassembled apparatus showing the prepreg stack and the EMAT probes in holders.

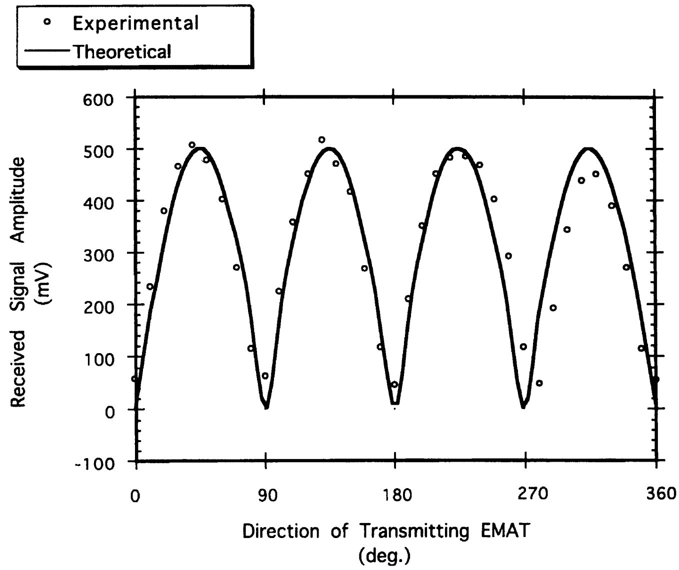


Fig. 5 Shear wave transmission through a 12-ply unidirectional uncured graphite-epoxy laminate using a pair of cross-polarized EMATs.

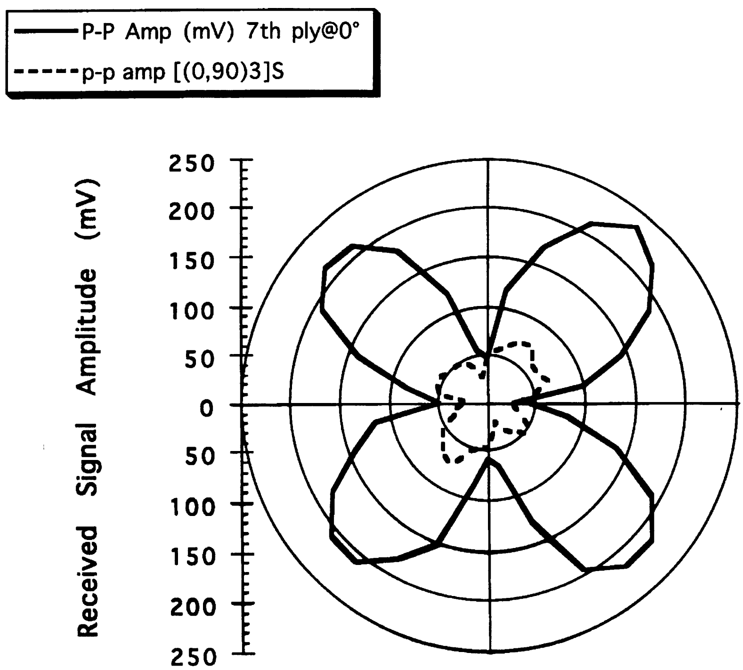


Fig. 6 Shear wave transmission through two 12-ply uncured graphite-epoxy laminates using a pair of cross-polarized EMATs.

CONCLUSIONS

Shear wave ultrasonics has not been fully exploited in the nondestructive evaluation of composite materials. In this work, it is demonstrated that shear waves, particularly the transmission of shear waves with the transmitter and receiver perpendicular to each other, have excellent sensitivity for detecting anomalies in fiber orientation and ply layup sequence that may occur in the manufacturing of composite parts. They can also be used as an indication of the quality of composite laminates and as a tool in the general study of material properties. In addition to using conventional piezoelectric shear wave transducers, EMATs were also used in the couplant-free generation and reception of shear waves. The EMAT technique can be applied to composite prepreg layups in their uncured state before autoclaving. Shear wave ultrasonics has shown sufficient capabilities to warrant further development into a practical NDE tool for composite manufacturing.

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